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A Numerical Technique to Correct Heat Release Rate Calorimetry Data for Apparatus Time Delay

D. D. Evans and L. H. Breden

Center for Fire Research
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Final Report

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A NUMERICAL TECHNIQUE TO CORRECT HEAT RELEASE RATE CALORIMETRY DATA FOR APPARATUS TIME DELAY

D. D. Evans[1] and L. H. Breden

Abstract

A numerical scheme is presented to correct heat release rate measurements made with the Ohio State University rate of heat release apparatus for the effects of inherent time delays in the measurement system. The magnitude of the correction is shown to increase with increasing rate of change in heat release rate. Illustrative heat release rate curves for particle board and balsa wood show that corrections to the peak heat release rate of 40% and 130% respectively are necessary. Measurements of the apparatus time response to step changes in heat release rate are reported. A simple method of determining corrections to the measured peak heat release rate is discussed.

Key words: Calorimetry; heat release rate; response time; time delay.

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[1] At the time this work was completed D. Evans was a Postdoctoral Research Associate for the National Research Council (NRC) at NBS.

1. INTRODUCTION

As part of the evolution in material fire performance testing, much attention has been given recently to the measurement of the rate of heat release from a material burned under various conditions. Although at present several different methods to measure the rate of heat release of materials are available [1][2], the most widely used is that developed by Smith at Ohio State University [2,3]. With this method, materials and products are tested for the rate of heat release and rate of visible smoke release when exposed to different levels of radiant surface heating. This Ohio State University rate of heat release calorimeter (OSU-RHR) measures as a function of time, the increase in temperature of air forced through the apparatus at a constant flow rate. The increase in temperature can be related to the rate of heat release from a burning test sample. In addition, a rate of smoke release is determined by measuring the obscuration produced by smoke in the exhaust gases. From each test, typically 10 minutes in duration, two curves may be produced; one showing the rate of heat release, and the second the rate of smoke release as a function of time. Proposals have been made to characterize the samples tested by selecting particular values such as the peak rate and the time to the peak rate from the experimental curves. In addition, an integration of the heat release rate curve is sometimes performed to measure the total heat released during the entire test or some portion of the test.

If one is interested in using the details of the heat release rate curves, he should be concerned with how closely the apparatus can follow changes in the rate of heat release from a sample. The slower the rate at which the apparatus can respond to fluctuating heat release rates, the more distorted the measured values will be from the actual rate of heat release from the sample. It is for this reason that Smith suggests that rate of heat release measurements from tests in which changes in

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[2] Numbers in brackets refer to the literature references listed at the end of this paper.

heat release rate greater than 220 J/s^2 (750 Btu/min^2) [2] occur not be considered a quantitative measurement of heat release rate and only be used for comparative purposes. Our work shows that a substantial distortion of the measured heat release rate as compared with the actual values is possible at rates of change of heat release rate well below the 220 J/s^2 (750 Btu/min^2) limit.

In this work, the time response characteristics of the OSU-RHR apparatus are reported. These are used in a simple numerical data analysis program to correct rate of heat release measurements for the distortions introduced by the time delays in the system. The corrected measurements are in all cases a better representation of the actual rate of heat release from a burning sample than the uncorrected data. Specific examples of corrected and uncorrected heat release data from tests using particle board, balsa wood and a programmed methane burner are presented. In addition a simple method of estimating the error in peak rate measurements because of time delay is discussed.

2. EXPERIMENTAL

A useful way to characterize the time response of the OSU-RHR apparatus is to examine the output that results from a step change in heat release rate input. For this investigation an effort was made to simulate as closely as possible, conditions that exist during material testing in the vertical position. Figure 1 shows a schematic representation of the equipment assembled within the test chamber of the OSU-RHR apparatus. In the standard vertical sample holder (0.152 m x 0.152 m) a 0.01 m thick mat of lightweight (Density = 100 kg/m^3 = 6 lb/ft^3) fibrous refractory insulation was mounted. No backing material was used as the insulation mat was sufficiently rigid to be held in place by the standard holder spring clip. The binder-free insulation mat simulates a sample in the holder, but releases no heat during the test. Heat release rate for the simulation was controlled by the methane flow rate to the burner along the bottom edge of the vertical holder. During time

response tests, visible flames from the burner would form a sheet along the insulation surface contacting and rising above the top edge of the holder. Visually this simulated what commonly occurs in routine testing of materials. The mass of the insulation mat used in the holder was small enough that no significant influence of it on the time response of the apparatus was expected.

The procedure for measuring the response of the OSU-RHR apparatus to step changes in heat release rate began by igniting a small pilot flow rate of methane through the burner. Enough time was allowed to stabilize a base line output of the apparatus to this small heat release rate. Each of the small pilot flames would grow rapidly when selected larger flow rates of methane gas were quickly added to the burner fuel supply, effectively producing a step change in heat release rate within the apparatus. Adding the increase fuel flow to the burner from a pressure regulated reservoir through a simple on-off valve produced a gas surge immediately after opening the valve. In trial runs, this surge of fuel above the steady flow rate value caused the apparatus to respond very quickly; the output reaching 90% of the steady value in about five seconds. To avoid fuel surges and achieve an acceptable step change in flow rate, increases in methane flow to the burner for our tests were made by switching the flow from a vented gas line to the burner fuel supply line. The vent line was constructed such that its resistance to gas flow was the same as the system supplying the burner, thus minimizing any gas surge in rapid switching of the gas flow between lines. Sharp step decreases in heat release rate were produced by simply shutting off the extra methane flow and returning to the base-line pilot flame flow rate.

The response of the OSU-RHR apparatus to two different levels of step increases and decreases in heat release rate ($\pm$1.51 kJ/s [86 Btu/min] and $\pm$3.87 kJ/s [220 Btu/min]) were measured at a 25 kJ/m^{2}s (2.5 W/cm^2) heat flux from the radiant panel determined at the face of the sample holder. This heat flux is the most widely used in our present testing.

In addition, the response to a third level of change ($\pm$4.57 J/s [260 Btu/min]) in heat release rate was measured with the radiant panel off. The results of these six measurements are shown in figure 2. Despite the fact that the response of the instrument appears slightly faster in the tests with the radiant panel off, the agreement between the six normalized responses is good. At 240 s (4 min) after the change in heat release rate was made, approximately 90% of the full response was measured. Full response was achieved after 1200 s (20 min).

Analytically the time response is represented well by the expression:

$$E(t) = 1 - \frac{1}{1.4}\left(e^{-t/8} + 0.4e^{-t/200}\right) \qquad (1)$$

where E(t) is the fraction of the total response with t measured in seconds. This expression suggests that the time response of the apparatus is a combination of a fast response possibly associated with the thermocouples and a slower response influenced by the mass of the apparatus.

3. ANALYSIS

Most OSU-RHR apparatus in operation today are augmented by digital data logging equipment with computerized data reduction. The continuous analog outputs from the apparatus are usually sampled by the data logging system once every few seconds and the data stored for later processing. In most cases processing of the data presently involves simple multiplication of raw data by appropriate calibration constants to produce data in acceptable units for tabulation and/or plotting as a function of time. The computer assisted data reduction while performing the above task efficiently can be further utilized to correct the data for apparatus time delay. While staying within the capabilities of the laboratory oriented mini-computer a better representation of the actual heat release rate of a tested material can be calculated from the test data.

There are several techniques that can be employed to correct heat release rate data. Smith and Heibel [4] employ a combination of a fast and slow dynamic correction. The fast correction is performed with a derivative lead compensation on smoothed experimental data, approximating the system response as first order and linear. The slow dynamic compensation utilizes a two parameter model of the system.

The method employed here uses the experimentally measured response to a step change in heat release rate directly to correct test data. It also exploits the fact that within acceptable accuracy the time response of the apparatus to a step change in heat release rate is insensitive to the magnitude and direction of the change, and to the panel heat flux. This fact, supported by experimental observations discussed in the previous section, justifies the treatment of the OSU-RHR apparatus as a linear dynamic system.

In a linear system, any overall system response may be represented as the sum of many partial responses. In particular, one may build up the time varying heat release rate output as the sum of many step inputs for which the response of the apparatus is known. Mathematically we may represent this statement by:

$$O(t) = \int_{0}^{t} \frac{dC(\tau)}{d\tau} E(t - \tau)\, d\tau \qquad (2)$$

where:

O(t) is the experimental output from the OSU-RHR apparatus,

C(t) is the actual heat release rate of the burning sample and may be thought of as the corrected output or corrected O(t),

E(t) is the measured fractional time response of the apparatus to a step change in heat release rate,

t is the time in seconds measured from the beginning of the test, and

τ is the dummy variable of integration.

For special cases of E(t) equation (2) may be solved exactly for the corrected output, C(t), in terms of O(t), the uncorrected experimental results. In particular, if E(t) results from a simple first order lag in the system $E(t) = 1 - \exp(-at)$, the solution would be:

$$C(t) = O(t) + \frac{1}{a}\frac{dO(t)}{dt} \tag{3}$$

Equation (3) is essentially the same as that used by Praul and Hmurcik [5] to correct thermocouple measurements for time lag.

For the case of the OSU-RHR, the response of the instrument to a step input, E(t), is given by equation (1). This case is more complicated than the simple first order lag system discussed above. An analytic solution to equation (2) for C(t) using equation (1) for E(t) can still be obtained but is considerably more complicated than equation (3) and involves second derivatives of the experimental curve O(t). These two factors render it impractical for direct use. Instead we have chosen to obtain and approximate solution to equation (2) numerically. The recursive calculation to be performed on experimental data, sampled at a fixed interval, to correct them for time delay associated with the apparatus will be developed from equation (2).

Writing equation (2) at time equal to $t + \Delta t$ yields:

$$O(t + \Delta t) = \int_0^{t+\Delta t} \frac{dC(\tau)}{d\tau} E(t + \Delta t - \tau)\, d\tau \tag{4}$$

Dividing the interval of integration into two parts and approximating $E(t + \Delta t)$ as $E(t) + \frac{\partial E}{\partial t}\Delta t$ gives:

$$O(t + \Delta t) = \int_{0}^{t} \frac{dC(\tau)}{d\tau} E(t - \tau)\, d\tau + \int_{0}^{t} \frac{dC(\tau)}{d\tau} \left(\frac{\partial E(t - \tau)}{\partial t} \Delta t\right) d\tau +$$

$$\int_{t}^{t + \Delta t} \frac{dC(\tau)}{d\tau} E(t - \tau)\, d\tau + \int_{t}^{t + \Delta t} \frac{dC(\tau)}{d\tau} \left(\frac{\partial E(t - \tau)}{\partial t} \Delta t\right) d\tau \tag{5}$$

Retaining only terms of order Δt or greater eliminates the last term on the right hand side of equation (5). Then recombining the first and second integral and approximating all integrals with summations yields:

$$O(t_{i+1}) = \sum_{j=0}^{j=i-1} \frac{C(t_j) - C(t_{j-1})}{\Delta t} E(t_{i+1} - t_j)\, \Delta t + \tag{6}$$

$$\frac{C(t_i) - C(t_{i-1})}{\Delta t} E(\Delta t)\, \Delta t$$

Solving for $C(t_i)$ gives for $i \geq 0$

$$C(t_i) = C(t_{i-1}) + \frac{O(t_{i+1}) - \sum_{j=0}^{j=i-1} \left[C(t_j) - C(t_{j-1})\right] E(t_{i+1} - t_j)}{E(\Delta t)} \tag{7}$$

with $C(t_i) = 0$ for $i < 0$

Equation (7) is the basis of the numerical technique used in our correction for OSU-RHR data. Notice that $O(t_i)$ are experimental points and that the experimental response of the apparatus to a step input, E(t), is used directly. The presence of the summation in equation (7) will result in a longer run time for this correction technique compared to that of Smith and Heibel's correction [4]. The direct use of the easily obtained response to a step input, E(t), makes our technique very easy to apply to any individual rate of heat release apparatus. In fact, if storage space is available, only the experimental values of E(t) at the time differences to be used in the calculation need be retained, thus eliminating the need to curve fit this data.

Using this technique, experimental heat release rate data may be processed to yield a better representation of the actual sample performance in the test. Specific comparisons between corrected and uncorrected test results will be presented in the next section.

4. TEST RESULTS

To verify that corrections to measured heat release rate curves using the above technique are meaningful, measurements were made on a controlled heat release rate input. For this modest effort, the controlled heat release rate input similar in shape to data for particle board was achieved using a rotameter to manually control the methane flow to the burner shown in figure 1. The heat release rate was manually matched to the input curve shown in figure 3 at five-second intervals with smooth transitions between points. In figure 3 the metered heat release rate curve is shown as the broken line rising at a rate of 22 J/s^2 (75 Btu/min^2), leveling off shortly at 930 J/s (53 Btu/min), then decreasing to 720 J/s (41 Btu/min) until the methane flow was shut off at 150 seconds after the beginning of the simulation. We feel that the desired input curve was reproduced to within ± 0.02 kJ/s (1.1 Btu/min) using the manually controlled rotameter to adjust the fuel flow rate.

Two measurements (corrected and uncorrected) of the controlled heat release rate curve are also shown in figure 3. The corrected data based on a five-second data sampling interval agrees well with the known input. The uncorrected curve shows the distortions introduced by the apparatus time delay. As the correction process enhances fluxuations in the uncorrected data, the corrected data can be made more attractive by smoothing techniques one of which is discussed by Smith and Heibel [4].

The peak rate of heat release, a commonly used parameter of each heat release rate curve, for the corrected data of 920 J/s (52 Btu/min) agrees well with the actual rate of 930 J/s (53 Btu/min). In contrast the uncorrected data has a peak rate of 690 J/s (39 Btu/min) approximately 26% below the actual rate. This discrepancy in measured and known peak rates of heat release occurs at the termination of a constant rate of change of heat release rate 1/10 the maximum limit given for quantitative measurements 220 J/s^2 (750 Btu/min^2) in the ASTM Draft Procedure [2].

Integration of each curve in figure 3 with time yields the total heat released by the sample during the test. This total energy release was found to be conserved among the three curves within estimated experimental and calculational errors, thus serving as an additional check on the calculation.

In detail, integration of the corrected data curve yields a total heat release of 102 kJ (97 Btu) during the test. This is in good agreement with the 98.6 kJ (93 Btu) total heat release calculated by integrating the uncorrected curve including the portion of the tail beyond 215 seconds not shown in figure 3. Of the total heat release calculated from the uncorrected curve, 23% is contributed by the long tail of the curve. Integration of the test input curve yields 105 kJ (99 Btu) total energy release which also compares favorably with the value calculated from the corrected data.

For illustrative purposes corrected and uncorrected heat release rate curves for balsa wood and particle board evaluated at 25 kJ/m^2s (2.5 W/cm^2) panel heat flux are shown in figures 4 and 5 respectively. Both sets of data were taken at four-second intervals. In each case the corrected curve is significantly above the uncorrected curve.

4.1. Approximating Peak Rate Adjustments

In the illustrations above, it is clearly seen that because of the inherent time delay associated with the measurement of heat release rate with the OSU-RHR apparatus, measured rates are commonly different from the actual rates of heat release. It has been shown that with a modest effort these differences can be corrected through a numerical analysis of test data. To determine if the correction procedure is necessary for any particular set of heat release test data, it would be useful to be able to simply approximate how much difference will exist between the uncorrected set of data and its corresponding correction. Under certain conditions that are commonly satisfied, a good approximation to the difference between corrected and uncorrected <u>peak</u> rates of heat release can be simply calculated. This predicted difference can be used as a guide in determining whether or not the uncorrected data can be used satisfactorily in a given situation.

To obtain approximation to the peak rate correction one should consider the testing of an idealized material that releases heat at a linearly increasing rate with time. For this material, the corrected data would be

$$C(t) = bt \tag{8}$$

where t = time in seconds

b = rate of change of the rate of heat release

To find the corresponding expected output from the OSU-RHR apparatus, one must solve equation (2) using equations (1) and (8) as:

$$0(t) \quad = \quad \int_{0}^{t} b \left[1 - \frac{1}{1.4} \left(e^{-(t - \tau)/8} + 0.4e^{-(t - \tau)/200} \right) \right] d\tau \qquad (9)$$

Equation (9) may be solved using Laplace transforms noting that the right hand side is a convolution integral:

$$0(t) \quad = \quad bt - \frac{80}{1.4} b \left(1.1 - 0.1e^{-t/8} - e^{-t/200} \right) \qquad (10)$$

Considering times greater than 10 seconds, the second term in the parenthesis may be neglected compared to the other terms in the parenthesis. With this constraint equation (10) becomes:

$$0(t) \quad = \quad bt - 57b \; (1.1 - e^{-t/200}) \qquad (11)$$

Usually experimental rate of heat release rate data show a rise from zero to a peak rate and then decay towards zero. Often a linear increase can be used as an approximation to the actual rise in heat release rate before the peak rate is reached. This rise to the peak rate is often of a duration greater than 10 seconds and thus equation (11) applies. During this rise in heat release rate, the exponential function in equation (11) does not vary greatly; therefore, the rate of change of the corrected heat release rate data, b, will be approximately equal to the slope of the experimental data, 0(t). For this approximation, the representative slope of the experimental data increasing to the peak rate will be used to obtain a value for b from the test data. Then the difference between the corrected and the experimental (uncorrected) peak rate of heat release becomes:

$$C(t) - 0(t) \quad = \quad \Delta RHR \quad = \quad 57b \; (1.1 - e^{-\Delta t/200}) \qquad (12)$$

where ΔRHR = approximate difference between the corrected and uncorrected peak rate.

Δt = the duration of the representative linear rise to the peak rate in experimental data (s).

b = the slope of the representative linear rise to the peak rate in experimental data (RHR/s).

This expression may be checked against the corrected and uncorrected curves for balsa wood and particle board. In the case of particle board, we find an approximately linear rise in uncorrected heat release rate at a rate of $b = 3.31$ kJ/m^{2}s^2 (17.5 Btu/ft^2 min/s) for a $\Delta t = 40$ seconds. We would expect from equation (12) that the difference between the corrected and uncorrected peak rates would be 53.1 kJ/m^{2}s (280 Btu/ft^2 min) which compares well with the 56.8 kJ/m^{2}s (300 Btu/ft^2 min) observed in figure 5. For balsa wood the linear portion of the rise to the peak rate is less than the 10 seconds suggested in the use of equation (12). Under these conditions, equation (12) is likely to be an underestimate of the difference in peak rates. From the uncorrected curve for balsa wood figure 4, the two parameters needed for equation (12) are $b = 11$ kJ/m^{2}s^2 (58 Btu/ft^{2}min/s) and $\Delta t = 8$ seconds. The estimated difference between the corrected and uncorrected peak rates is 87 kJ/m^{2}s (460 Btu/ft^{2}min) which is low compared to the 117 kJ/m^{2}s (620 Btu/ft^{2}min) shown in figure 4.

It has been shown that equation (12) provides a good rule of thumb to estimate the expected difference between measured and actual rate of heat release from materials tested in the OSU-RHR apparatus.

5. CONCLUSIONS

The time delay inherent in heat release rate measurements made with the OSU-RHR (containing electric muffle furnace radiant panels) has been quantified by measurements of the apparatus response to step changes in heat release rate.

It has been demonstrated that the apparatus time delay is often responsible for the introduction of significant distortions in the measurement of heat release rate from burning materials. These distortions can occur in tests in which the rate of change of heat release rate is well below the presently accepted limit for quantitative measurements of 220 J/s^2 (750 Btu/min^2).

A numerical technique has been shown effective in correcting experimental heat release rate measurements from vertical material tests for the effects of the apparatus time delay.

A simple analytic expression has been developed to estimate peak rate of heat release corrections. This expression can serve as a tool to aid the researcher in making a judgment about the necessity of correcting a given set of experimental data.

6. ACKNOWLEDGMENTS

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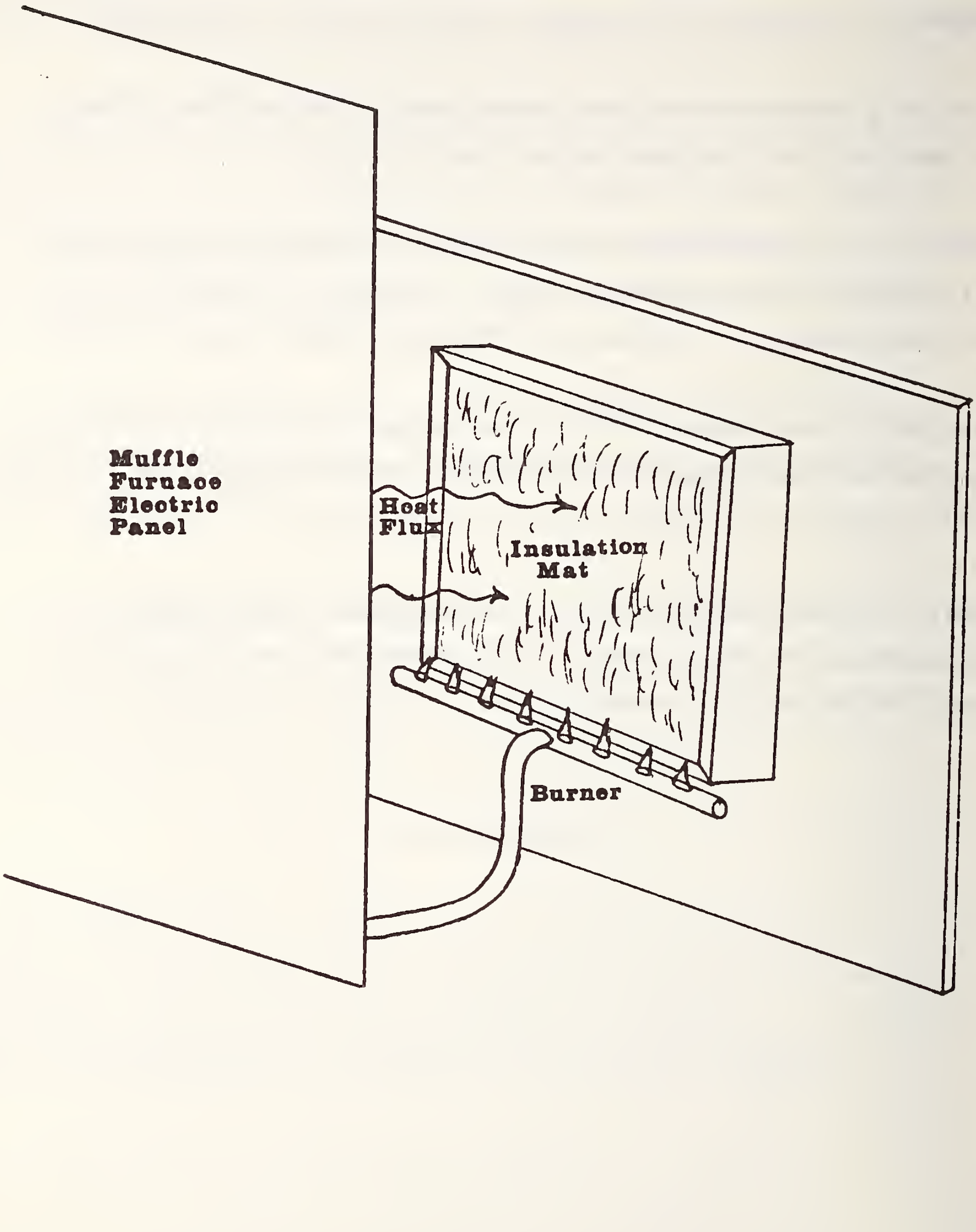

Figure 1. Test Assembly for Time Response Measurements

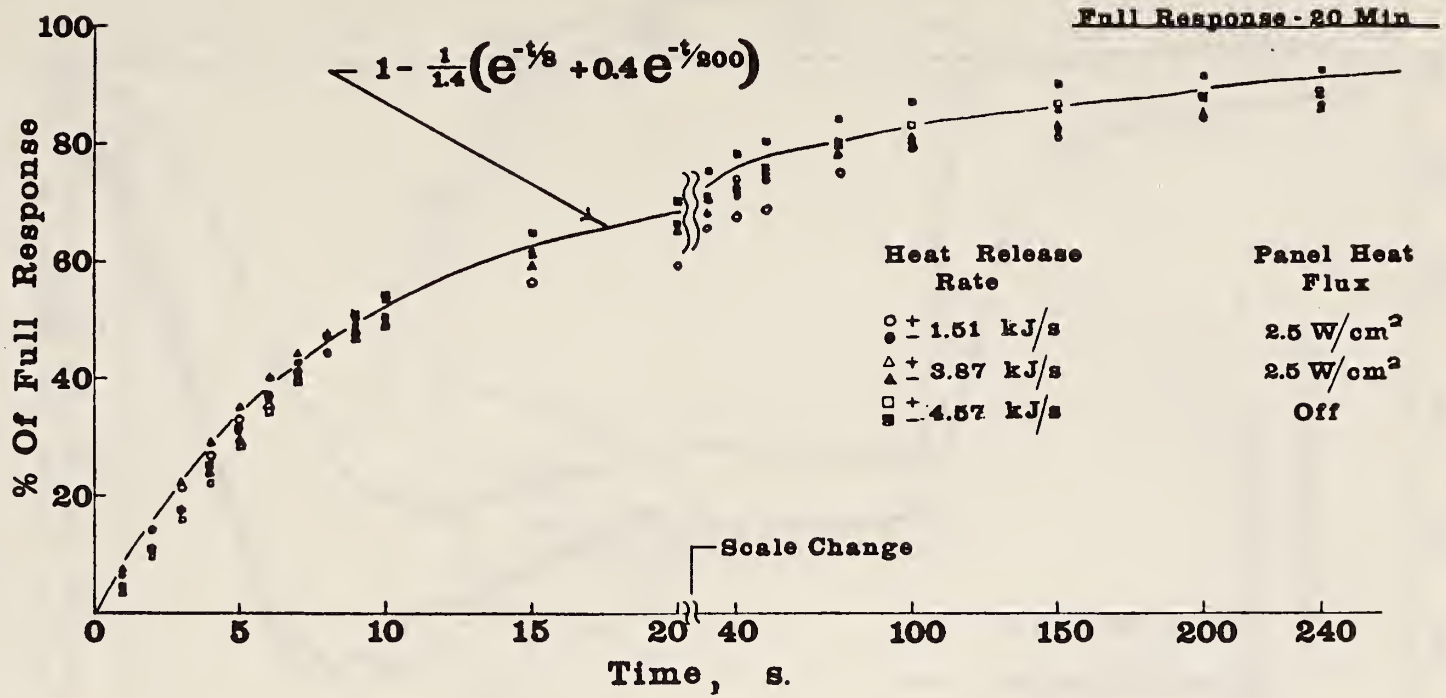

Figure 2. Normalized Time Response Data

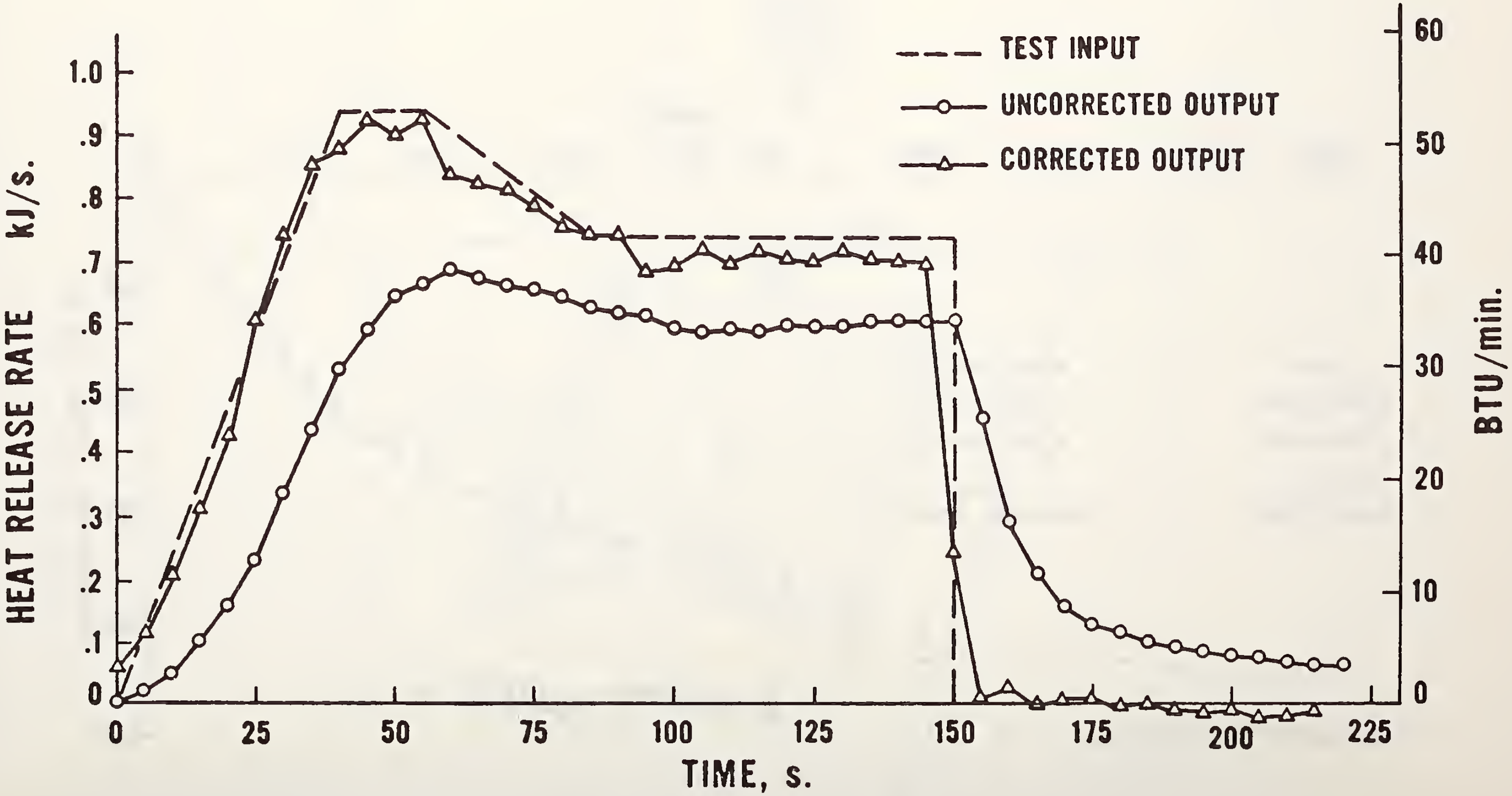

Figure 3. Dynamic Test Similar to Particle Board

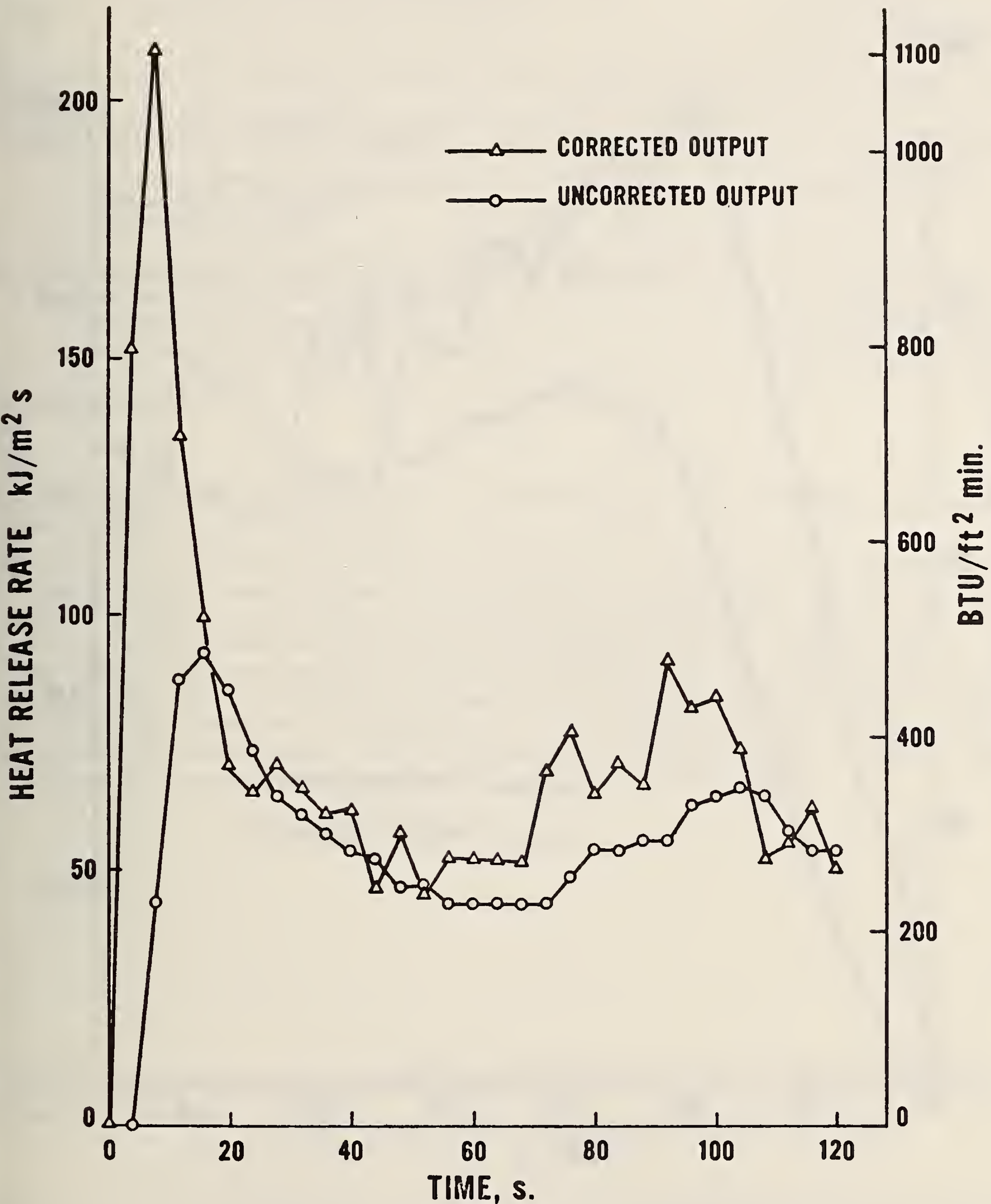

Figure 4. 13 mm Balsa Wood 2.5 W/cm^2

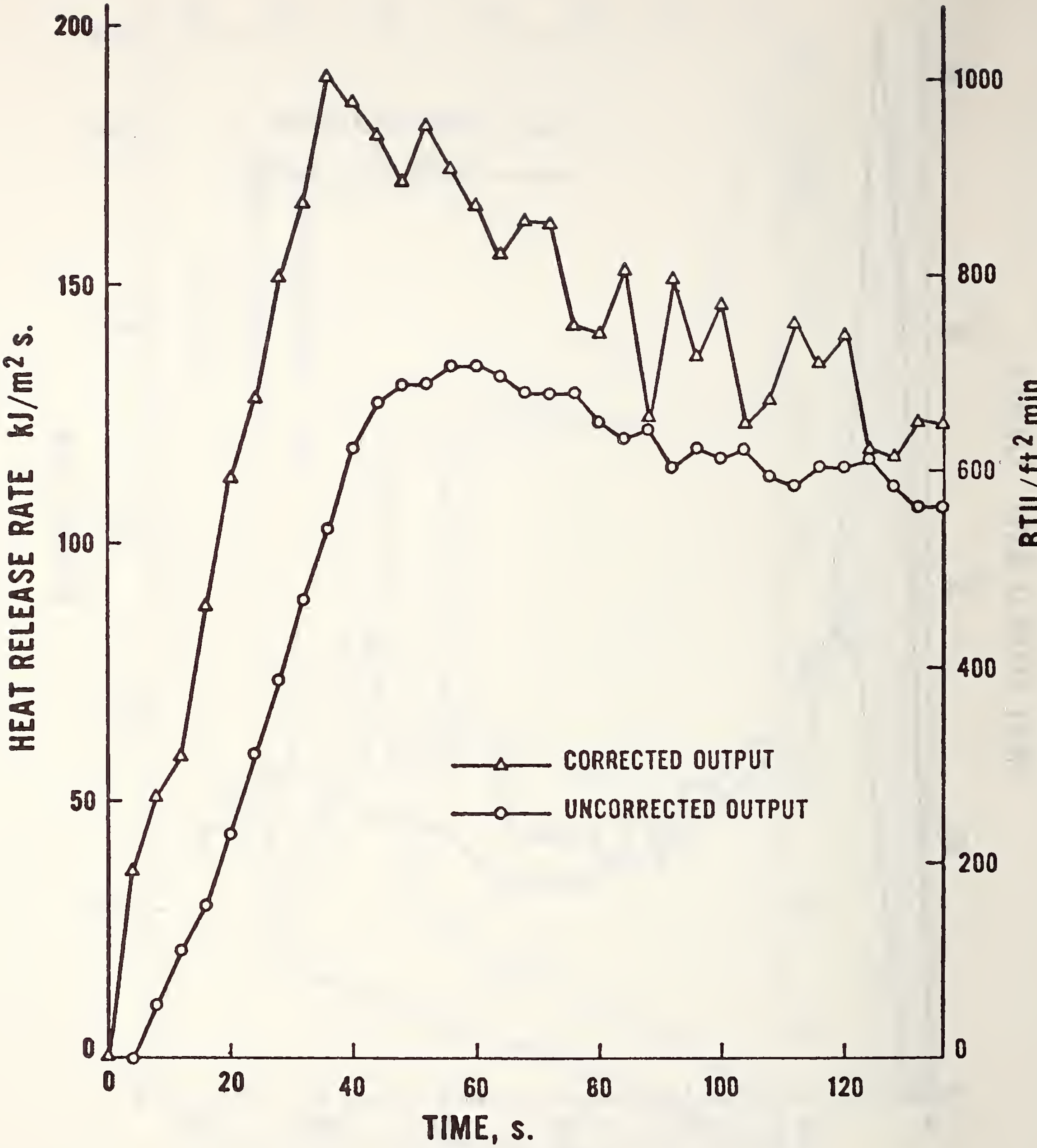

Figure 5. 19 mm Particle Board 2.5 W/cm^2

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A numerical scheme is presented to correct heat release rate measurements made with the Ohio State University rate of heat release apparatus for the effects of inherent time delays in the measurement system. The magnitude of the correction is shown to increase with increasing rate of change in heat release rate. Illustrative heat release rate curves for particle board and balsa wood show that corrections to the peak heat release rate of 40% and 130% respectively are necessary. Measurements of the apparatus time response to step changes in heat release rate are reported. A simple method of determining corrections to the measured peak heat release rate is discussed.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Calorimetry; heat release rate; response time; time delay.

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